Colorfulness enhancement in λSY color space

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Abstract

The aim of this paper is to propose a new strategy to both enhance the colorfulness of a color image and to improve its contrasts by using the full RGB color gamut. Colorfulness can be seen as a global perceptual attribute which is highly correlated to the average chroma. This new strategy consists to extend image color gamut by performing saturation increasing in the λSY color space. In order to analyse and to describe color image changes, we have chosen to represent color images according to their color point distribution in the xyY color space.

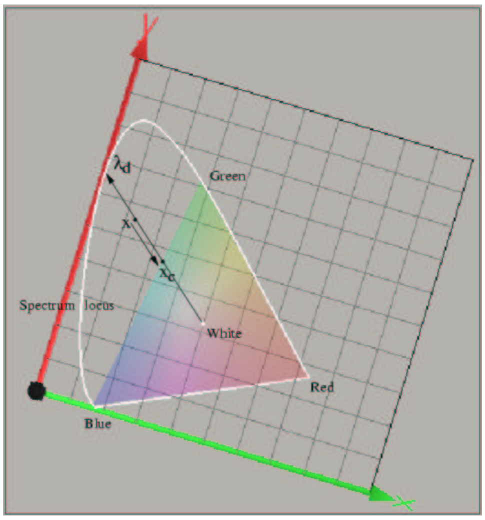
Introduction

Colorfulness can be seen as a global perceptual attribute which is highly correlated to the average chroma. To enhance the average chroma, or the average saturation, of an image different strategies had been used [1,2,3]. Considering that the Human Visual System (HSV) is more sensitive to chromatic changes than to luminance changes, and that we can perform natural-looking images by enhancing saturation component meanwhile leaving the hue component unchanged, we propose to use a new strategy which consists to extend image color gamut by performing saturation increasing in the λSY color space. In order to analyse and to describe color image changes, we have chosen to represent color images according to their color point distribution in the xyY color space.

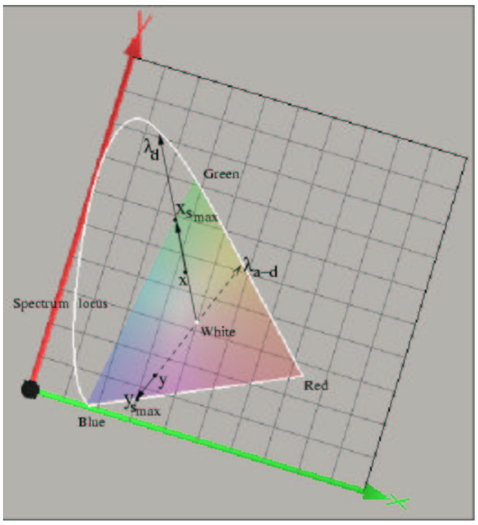
λSY color space

It is generally agreed that the perceptual attributes of color can be described by Luminance (L), Hue (H) and Saturation (S). Luminance is achromatic and describes the brigthness of the image. Hue and Saturation are the chromatic components: Hue represents the dominant wavelength and Saturation represents the amount of white mixed with the pure color.

In this study, we have used another color space representation, more relevant than the HSV color space representation, based on brightness, dominant wavelength and saturation attributes: the λSY color space. λSY color coordinates are defined from xyY color coordinates according to the following principles.



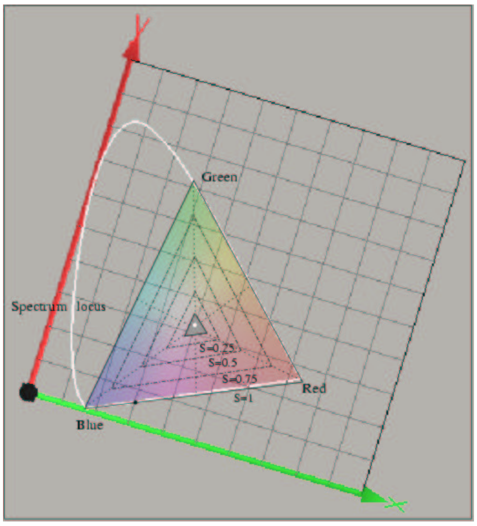
(a) clipping of the color gamut (from X to X_c) based on a mapping process in the opposite direction of the dominant wavelength.



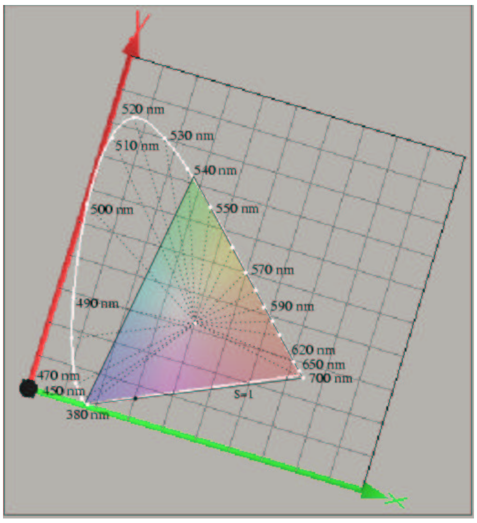
(b) spreading of the color gamut from dominant wavelength (from X to X_s), or anti-dominant wavelength (from Y to Y_s)

Figure 1: Color changes in the xy chromaticity diagram.

Let us consider the xy chromaticy diagram displayed in Figure 1(b). Any real color X that lies within the region enclosed by the spectrum locus line and upper the lines BW and WR can be considered to be a mixture of illuminant W and spectrum light of its dominant wavelength λ_d which is determined by extending the line WX until it intersects the spectrum locus [4].



(a) constant-value scale of saturation in xy chromaticity diagram



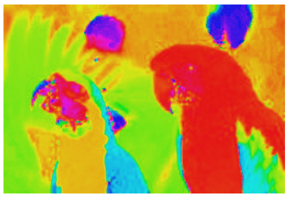
(b) constant-value scale of dominant wavelength in xy chromaticity diagram

Figure 2: Color areas in the xy chromaticity diagram.

Any color Y that lies on the opposite side of the illuminant point and below the lines BW and WR can be described by an anti-dominant wavelength λ_{a-d} which is determined by extending the line YW until it intersects the line BR (i.e. the *purple line*).

The saturation S is determined in the xy chromaticity diagram for the former case (i.e. case X) by the relative distance of the sample point and the corresponding spectrum point from the illuminant point, and for the latter case (i.e. case Y) by the relative distance of the sample point and the corresponding purple point from the illuminant point. Let us consider that:

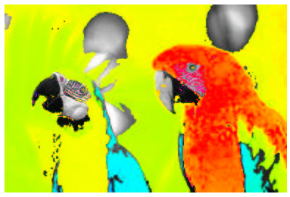
$$\begin{array}{ll} S \text{ is positive for case} & X \\ S \text{ is negative for case} & Y \end{array}$$



(a) H of HSV

(b) S of HSV

(c) V of HSV



(d) λ of λSY

(e) S of λSY

(f) Y of λSY

Figure 3: (a) H component displayed with a spectral LUT, (b) and (c) S and V components displayed with a gray LUT. (d) λ component displayed with a spectral LUT (when λ is undefined, the corresponding achromatic value is displayed with $S = 0$), (e) and (f) S and Y components of λSY displayed with a gray LUT. In order to display the λ component with a "true color" Look Up Table (LUT), we have used the algorithm of Bruton [6].

Another strategy may consist to assign a saturation of 100% to each color that lies on the triangle defined by the lines BG, GR and BR which delimitates the gamut of colors of all possible mixtures of a given set of three primary colors (see figures 2(a) and 3(e)).

In the case of the purity of a color Z is too small, e.g. lesser than 10%, the color can be considered as achromatic (*hueless*).

Consequently (see figure 3(d)), we can consider that:

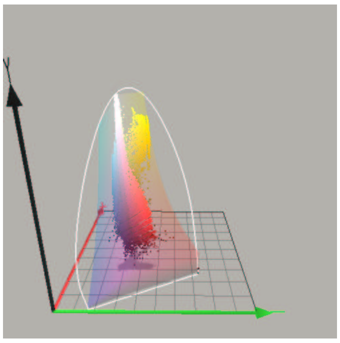
$$\begin{array}{ll} \lambda = \lambda_d & \text{if } S > \alpha\% \\ \lambda = \lambda_{a-d} & \text{if } S < -\alpha\% \\ \lambda \text{ undefined} & \text{if } |S| \leq \alpha\% \end{array}$$

When λ is "undefined", by default we can consider that $\lambda = \lambda_d$ if $S > \alpha\%$, otherwise $\lambda = \lambda_{a-d}$.

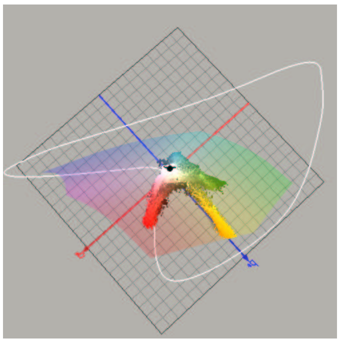
Different values of α ($5\%, 10\%, 15\%$ and 20%) have been tested in this study. Results obtained have confirmed than $\alpha = 10\%$ enables to delimitate quite correctly the achromatic area corresponding to the "white zone" of the Kelly's diagram [5].

Y characterizes the brightness, its corresponds to the luminance attribute of the xyY color space (see figure 3(f)).

(a) RGB image



(b) xyY color space



(c) $L^*a^*b^*$ color space

Figure 4: (a) RGB image displayed with a "true color" Look up Table (LUT), (b) colors distribution in the xyY color space, (c) colors distribution in the $L^*a^*b^*$ color space.

Relevance of colorfulness as perceptual attribute

It is generally agreed that the color gamut of most of RGB color spaces corresponding to output devices are lesser than the color gamut of the CIE 1931 or CIE 1964 XYZ color spaces, because a color output device can only produce a limited amount of colors and because the color mixing principles used are different. In order to reproduce RGB colors which do not belong to the XYZ color gamut, different color gamut algorithms based on color clipping can be used [7] (as example, see figure 1(a)).

In order to judge the relevance of an image color gamut extending, different perceptual attributes can be used such as colorfulness, naturalness and perceptual quality [8,9,2]. Among these, colorfulness is defined as presence and vividness of colors in the whole image. Colorfulness is a global perceptual attribute which is highly correlated to the average chroma ΔC^* [8]. ΔC^* values can be computed from the $L^*a^*b^*$ color coordinates (see figure 4) from $C^* = \sqrt{a^{*2} + b^{*2}}$.

To analyse and to describe the differences of chroma (i.e. differences of colorfulness) between two images, e.g. before and after saturation enhancement, we have computed the differences of average chroma and of variability (standard deviation of chroma) between each pair of corresponding pixels. The differences in lightness and hue between corresponding pixels have been also computed.

Saturation increasing

In order to enhance the colorfulness and the chromaticness of a given image, we have developped four methods increasing the saturation S of the color of each pixel in the direction of its dominant wavelength λ [10], this without changing its hue.

The first solution consists to increase the saturation proportionally to the original saturation value, except for achromatic colors which stay unchanged, such as:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} -> \begin{pmatrix} x \\ y \\ Y \end{pmatrix} -> \begin{pmatrix} \lambda \\ S \\ Y \end{pmatrix} -> \begin{pmatrix} \lambda \\ S_{adjusted} \\ Y \end{pmatrix}$$

$$-> \begin{pmatrix} x_{adj} \\ y_{adj} \\ Y \end{pmatrix} -> \begin{pmatrix} R_{adj} \\ G_{adj} \\ B_{adj} \end{pmatrix}$$

with $S_{adjusted} = S + \beta\%\, S$, considering that if $S_{adjusted} > S_{max}$ then the color is necessary clipped.

This process consists to multiply the saturation component by a constant.[1] This process leaves the hue and the luminance unchanged (see figure 7). Different values of β (50, 100 and 150) have been tested in this study.

The second solution consists to expand the saturation component to the maximum saturation of each input color saturation, considering that the maximum saturation is a function of both hue and of luminance, defined by $S_{max} =$

[1] The same strategy was also used in [8,2].

$f(\lambda, Y)$.[2] This process can be described as follows:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} -> \begin{pmatrix} x \\ y \\ Y \end{pmatrix} -> \begin{pmatrix} \lambda \\ S \\ Y \end{pmatrix} -> \begin{pmatrix} \lambda \\ S_{max} \\ Y \end{pmatrix}$$

$$-> \begin{pmatrix} x_\lambda \\ y_\lambda \\ Y \end{pmatrix} -> \begin{pmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{pmatrix}$$

where (x_λ, y_λ) are the xy chromaticity coordinates of (λ, S_{max}) color point (see figure 1(b)).

This process leaves the hue and the luminance unchanged (see figure 6). We can compare this second process to an "histogram explosion" which greatly improves color contrasts rather than preserving perceptual qualities [11].

The aim of the third solution is to amplify the saturation increasing without getting out of the gamut of colors available for a given set of three primary colors. It consists firstly to decrease the luminance component such as $Y_{adjusted} = Y - \gamma\%\ Y_{max}$ (Resp. $= Y + \gamma\%\ Y_{max}$), next to increase (i.e. to multiply) the saturation component proportionally to the original saturation value, such as done in the first method. This third solution can be described as follows:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} -> \begin{pmatrix} x \\ y \\ Y \end{pmatrix} -> \begin{pmatrix} \lambda \\ S \\ Y \end{pmatrix}$$

$$-> \begin{pmatrix} \lambda \\ S_{adjusted} \\ Y_{adjusted} \end{pmatrix} -> \begin{pmatrix} x_{adj,\lambda} \\ y_{adj,\lambda} \\ Y_{adjusted} \end{pmatrix} -> \begin{pmatrix} R_{adj,\lambda} \\ G_{adj,\lambda} \\ B_{adj,\lambda} \end{pmatrix}$$

This process leaves the hue unchanged and changes quite imperceptibly the luminance. This process leaves the achromatic color unchanged (see figure 8). Different values of γ (2.5 and 5) have been tested in this study.

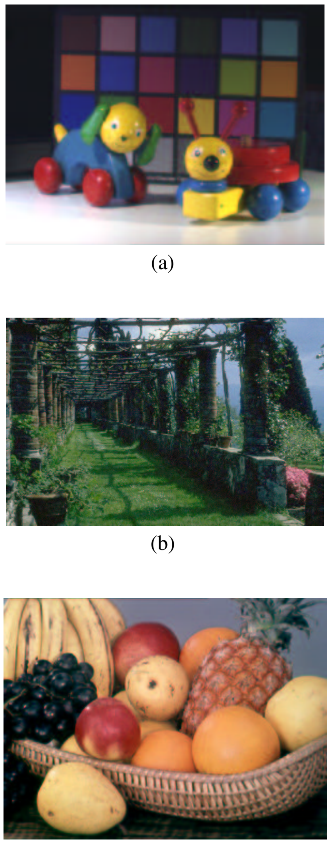
The latest solution consists to mix the second and the third methods, firstly in decreasing the luminance component and next in expanding the saturation component to the maximum saturation corresponding to the $Y_{adjusted}$ value, considering that the maximum saturation corresponding to a given wavelength increases when the luminance value decreases. Different values of β and γ have then been tested in this study.

Experiments and Results

A set of four test images have been used to study the performance of each of these color enhancement methods in order to minimize the influence of test images choice [12].

[2]The maximum saturation becomes smaller as the luminance approaches the extreme values of white and black for which the saturation is zero.

A new set of images had been created by varying the chroma value of each pixel in changing saturation component, as proposed in previous section using different α, β and γ values, while the lightness and hue component were kept constant (as example, see figures 6, 7 and 8). Our objective was also to check the relation between colorfulness and chroma.



(a) (b) (c)

Figure 5: Other original images tested.

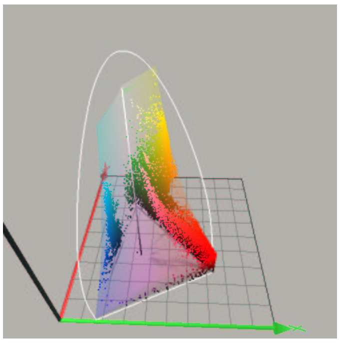
Two experiments was done to analyse the relevance of the color enhancement methods proposed in regards to perceptual attributes. Four subjects participated in the experiments. They had normal or corrected-to-normal visual acuity. The subjects viewed the CRT monitor calibrated and placed in a darkened room at a distance of about 1.7m. At this distance, the pixel size is about 1 min of arc. In one experiment, subjects were asked to judge the "perceptual quality" and "naturalness" of the images on a ten-point numerical category scale ranging from one (lowest attribute strength) to ten (highest attribute strength).[3] In a second experiment, subjects were asked to scale the "colorfulness" of the same images.[4]

[3]Fedorovskaya et al. showed in [8] that there is a high degree of correspondence between "perceptual quality" and "naturalness".

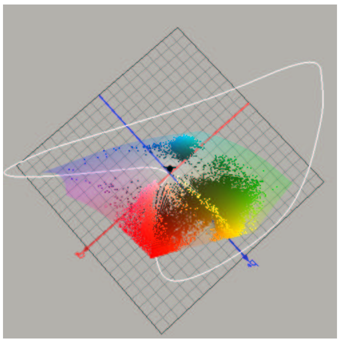
[4]Fedorovskaya et al. showed in [8] that there is a high degree of cor-

The images were displayed on the black screen for 5 s, while the interval between two images exposures was at least 3 s during which a 10 cd/m2 gray adaptation field with the chromaticity coordinates of D65 appeared on the screen. The image and adaptation field had the same size. Before starting a session, the subjects judged a training series of 29 images. Each experiment consisted of one session in which 87 images were presented three times in a random sequence.

(a) S->S_{max}



(b) xyY color space



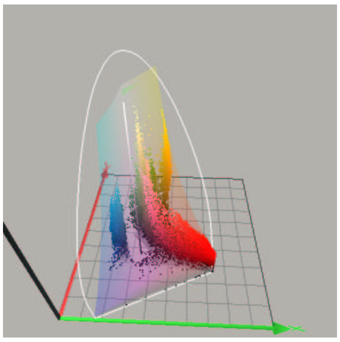
(c) $L^*a^*b^*$ color space

Figure 6: Results of saturation increasing (with $\alpha = 15\%$). (xy representation are viewed from the positive luminance axis.)

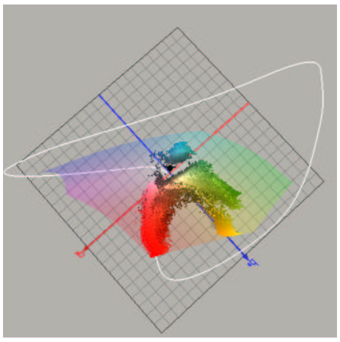
The first results obtained confirm that observers have a subjective preference for more saturated, indeed, more colorful image, and that limited colorfulness enhancement enables higher perceptual quality (e.g. $\alpha = 10\%$, and $\beta = 50$ or $\gamma = 2.5$). A similar observation was already reported by other works [8, 2, 3]. Likewise, we have observed that a too important colorfulness enhancement (e.g. $\alpha < 10\%$, and $\beta > 100$ or $\gamma > 2.5$) could lead to a reduction in perceptive quality due to a resulting decrease in naturalness. Moreover, these experiments have shown that the absence of low-saturation colors gives the image an unnatural appearance. Lastly, we have observed that the increased saturation could produce hue noise in uniform areas and that features in the "background" undetectable in the original image could become apparent.

respondence between "colorfulness" and "perceptual quality" in some cases of chroma variations.

(a) S->50%S for $Y - 5\%Y_{max}$



(b) xyY color space



(c) $L^*a^*b^*$ color space

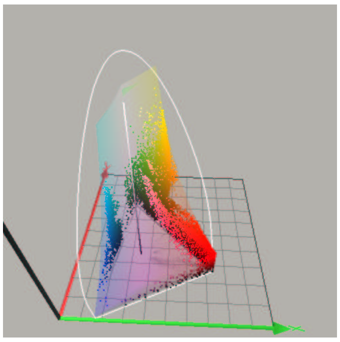
Figure 7: Results of saturation increasing (with $\alpha = 15\%$). (xy representation are viewed from the positive luminance axis.)

These experiments have shown a weak dependence between image contents and chroma changes. Such a result was already shown by Sano et al. [2]. We have also observed a weak dependence between image contents and lightness changes (with the 3^{rd} method) when lightness changes are limited (e.g. when $\gamma < 2.5$).

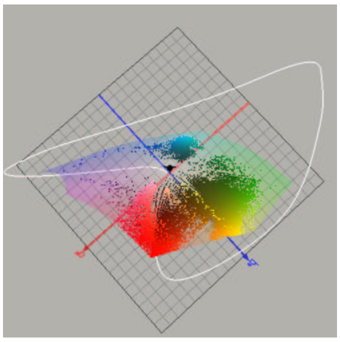
Lastly, these experiments have shown that the method which gives the better results was the third one (when

$\gamma = 2.5$ and $\beta = 50$). It is also interesting to note that in some cases of study resulting images reveal objects not visible in the original image while maintaining a natural appearance. This latter effect confirm that the saturation increasing can play an important role in the extraction of edges features for a color image [13, 1].

(a) S->S_{max} for $Y - 5\%Y_{max}$



(b) xyY color space



(c) $L^*a^*b^*$ color space

Figure 8: Results of saturation increasing (with $\alpha = 15\%$). (xy representation is viewed from the positive luminance axis.)

Conclusion

In this paper four methods have been proposed to enhance the colorfulness of an image in extending its color gamut in λSY color space. Different parameters have been proposed and tested to control the saturation increasing in regards to perceptual attributes.

The consistency of subjective preference that was found in this study supports the approach of systematic transformation of images on the basis of different attributes of color perception for optimization of color image rendering or enhancement of color image contrast.

The next step of this study will consist to establish perceptibility thresholds for each parameter in regards to various color-difference formulae.

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Biography

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Alain Trémeau is at the head of LIGIV (http://www.ligiv.org), a research laboratory working on computer Graphics, Vision Engineering and Color Imaging Science. He is currently mainly focused on mathematical imaging and color science with reference to human vision and perception. He works also in color metric with regard to color appearance and rendering measurements. He has written numerous papers or book chapters on Computational Colour Imaging and Processing. He is at the head of the *French Color Imaging Group*.